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5. SINGULARITIES OF THE URBAN CLIMATE OF ŁÓDŹ, CENTRAL POLAND

5.1. Introduction

Modification of the local climate by the cities is one of the best documented and unquestionably man's influences on the climate. The most striking feature of the urban atmosphere is air pollution, which was documented already in ancient times and still is a vital problem in many urban areas. At the beginning of the 19th century, L. Howard pointed out that meteorological parameters, namely temperature, can also be modified by urbanisation. His finding that nights in the centre of London are warmer than in the country is now known as the urban heat island phenomenon which has been a subject of numerous studies. Similarly, the influence of the city on

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other meteorological parameters and physical processes leading to the contrasts formation have been extensively investigated over the past 150 years. In Poland, some information on the singularities of urban climate can be found in the writings from the early 20th century, however, regular studies focused on these problems began in the 1960s. Łódź has been one of the leading centres in the country regarding such investigations (Fortuniak 2005). Since 1984, the Department of Meteorology and Climatology, University of Łódź, has regularly organised conferences “Urban Climate and Bioclimate” (in the years 1984, 1992, 1997, and 2007) and in 2003 we were the host institution of the 5th International Conference on Urban Climate organised by the International Association for Urban Climate.

The main goal of the present work is to review the key findings concerning the impact of urban development on local climate based on our over 50-years long investigations in Łódź. We refer to the urban heat island phenomena, urban-rural contrasts of humidity and wind speed, radiation processes at urbanised areas, urban energy balance, net exchange of the carbon dioxide and methane, and concentration of the radon gas.

5.2. Area of investigation and measurements sites

Łódź is the third biggest city in Poland in terms of population (ca 720 000). The topographical setting of the city, its size and building structure makes Łódź an exceptionally good place for studies on modifications of local climate by urbanisation. It is located in central Poland on the Great European Plain (51°46'N, 19°27'E). The city occupies a relatively flat area where differences of ground level over the entire built-up area are no more than 55 m (altitudes range between 180 and 235 m a.s.l. from south-west to north-east). The lack of big rivers, lakes, mountains, or other geographical peculiarities allows for detection of relatively undisturbed urban effect (Figure 5.1). The city's urban arrangement is very regular. In the city centre, the buildings were mostly constructed about 100 years ago, during the

period of rapid urban development resulting from a boom in the textile industry. As in many mid-European cities, they make up a large, homogenous and compact settlement of great density with a clearly marked roof level at a height of 15–20 m (Kłysik 1996, Kłysik and Fortuniak 1996, Fortuniak et al. 2001, Fortuniak 2003a, b, Offerle et al. 2005, 2006a, b, Pawlak et al. 2011, Fortuniak et al. 2013).

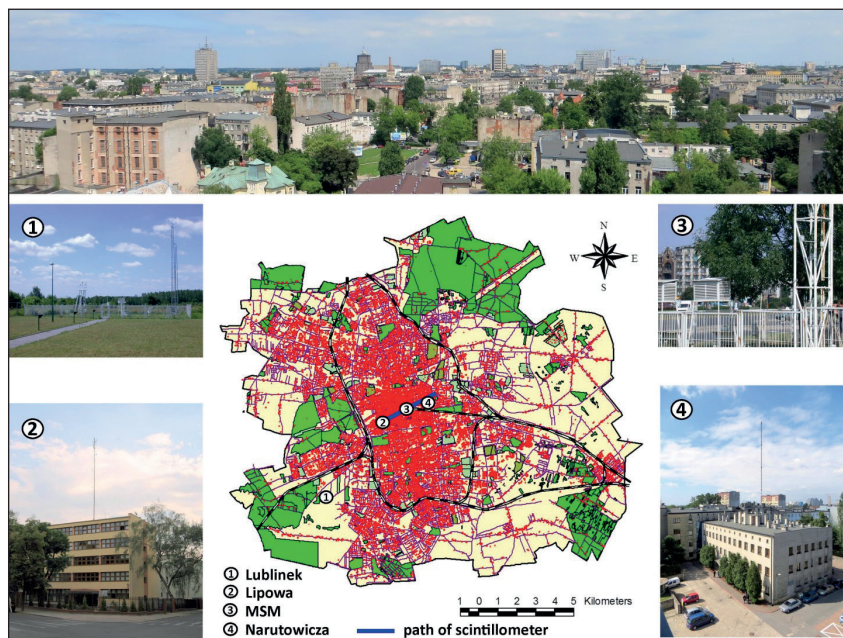


Figure 5.1. Location of the measurement sites in the area of Łódź and panorama from the top of Lipowa mast

Source: own elaboration

The anthropogenic heat emission estimated by Kłysik (1996) from the whole built-up area (spatial average) ranges from $12 \text{ W}\cdot\text{m}^{-2}$ in July to $54 \text{ W}\cdot\text{m}^{-2}$ in January. The values calculated for the central districts have a mean flux of $40 \text{ W}\cdot\text{m}^{-2}$ from $18 \text{ W}\cdot\text{m}^{-2}$ in July to $71 \text{ W}\cdot\text{m}^{-2}$ in January (Figure 5.2). Even if these estimations are based on the data

from the time before introduction of a number of technical and administrative solutions oriented to the reduction of energy consumption, they are in the range typical for the mid-latitude cities (Szymanowski 2004).

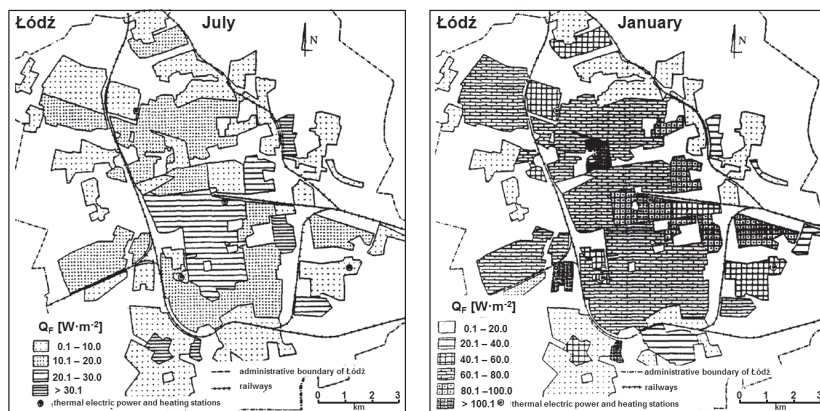


Figure 5.2. Mean anthropogenic heat flux in Łódź in July and in January

Source: K. Kłysik (1996)

The earliest meteorological data, which can be used for studies on the urban climate of Łódź date back to 1930s. Since 1930, the airport weather station Łódź-Lublinek (hereafter called Lublinek) has operated at some distance from the city centre, and it can be regarded as a reference rural station. In 1934–1939, there was a meteorological station in the city centre (Sienkiewicz Park) with dense development. The urban meteorological station (MSM) of the Department of Meteorology and Climatology, located in the very centre, operated from 1992 to 2012 when it was closed because of rebuilding of the main railway station. In 1996, the measurements were automated and the additional urban site was set at 81 Lipowa Street in the western edge of the old core of Łódź, next to the building of the Institute. The basic meteorological parameters were collected in 10-minute intervals at all three sites (Lublinek, MSM, Lipowa), which

allowed for detailed urban-rural comparisons (Figure 5.1). In the recent years, the eddy-covariance (EC) flux measurements including energy balance and greenhouse gas exchange have become one of the main subjects of our studies. The first open-path EC system in Łódź was installed in cooperation with Sue Grimmond and Brian Offerle (then of Indiana University) in November 2000 at the top of a 20 m high mast. The mast is mounted on the roof of a building (17 m) at Lipowa Street which is at least as tall as the surrounding ones, so the measurement height (37 m) is close or just above the blending height. The system worked up to September 2003. The new EC system has been working at the same place since July 2006. It is equipped with a Li-7500 infrared CO₂/H₂O gas analyser enabling estimation of the net carbon dioxide flux in parallel with the energy balance components. The second EC tower was set in June 2005 at the building of the Faculty of Geographical Sciences at 88 Narutowicza Street in the eastern edge of the old core of Łódź. The site is situated about 2.7 km east from the first one in a slightly less compact settlement. The mast (25 m) is mounted on the roof of a 16 m building, so the measurement height is almost 42 m, which is expected to be just above the roughness sub-layer. A new technique of estimation of the path-averaged turbulent sensible heat flux is scintillometry. A large aperture scintillometer (BLS900) operated in Łódź from September 2009 to November 2012 on the path 3142 m over the city centre. The transmitter was located at the mast on the Lipowa site and the receiver on a high building (36 m) in east direction. Besides the above mentioned long-term measurements, short-term observations were made in different campaigns focused on specific tasks.

5.3. Urban heat island (UHI)

The urban heat island is the best known modification of the local climate by urbanisation. It can be generally defined as an increase of temperature in a city in comparison to its surroundings. This phenomenon can be observed both in the near ground air layer (the canopy

layer UHI which is the subject of this study), as well as in the atmosphere above the city (the boundary layer UHI). T.R. Oke (1982) indicates eight commonly hypothesized causes of the canopy layer UHI: increased absorption of short-wave radiation due to multiple reflection in urban structures, increased long-wave radiation from the sky due to greater absorption and re-emission from polluted air above the city, decreased long-wave radiation loss being a result of reduced sky view factor, anthropogenic heat source, increased sensible heat storage in construction materials, decreased evaporation from construction materials, and decreased total turbulent heat transport. The canopy layer UHI (hereafter called just UHI) is a dynamical phenomenon which develops during the night (Figure 5.3). Four stages can be distinguish in the typical diurnal course of the UHI intensity in Łódź:

- During the day, the urban-rural thermal contrasts are small or even negative.
- Late afternoon temperature at rural station starts to drop faster than in the city centre and the thermal contrasts grow fast.
- About midnight, the cooling ratio at rural stations slows down, UHI stabilises and remains roughly constant throughout the rest of night.
- Just after sunrise, a rapid increase in temperature, especially at rural stations, results in a very fast decay of UHI.

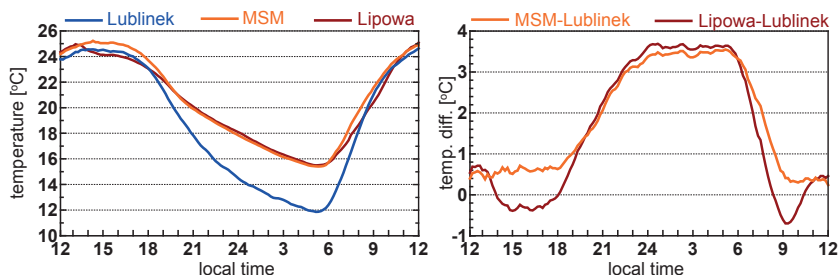


Figure 5.3. Typical evolution of temperature at rural (Lublinek) and urban (MSM, Lipowa) stations (left plot) and urban-rural differences (right plot). Average values for 28 selected days from August in Łódź, 1997–2002

Source: own elaboration

This general pattern is very similar in all seasons (Fortuniak et al. 2006). It differs from the well-known scheme presented by Oke (1995) which suggests the maximum of the UHI before midnight and a slow decrease after that. Under favourable weather conditions, the urban-rural temperature differences can reach a few or even around ten degrees. The highest values of UHI are observed during cloudless calm nights when less intensive cooling within the urban structures results in a relative temperature increase. The typical UHI intensity in Łódź under such conditions reach 4–7°C in summer and 2–3°C in winter (Kłysik and Fortuniak 1999, Fortuniak et al. 2006); however, the highest values of urban-rural temperature differences (8–9°C) do appear from time-to-time in the winter season (Figure 5.4). The intensification of wind speed, v and cloudiness, N , significantly reduce the UHI intensity. For Łódź, the maximum wind velocity which still preserves the urban heat surplus (i.e. when the urban/rural temperature differences exceed 1°C), is about $4 \text{ m}\cdot\text{s}^{-1}$ (Figure 5.5). Different types of function have been proposed to describe the dependence of UHI intensity on these two parameters. The most common is the linear (or quadratic) proportionality of maximum urban-rural temperature contrasts at night, ΔT_{max} , to cloudiness and inversed proportionality to the square root of wind speed: $\Delta T_{max} = c(N) \cdot v^{-1/2}$. However, our investigations show that the exponential function: $\Delta T_{max} = a(N) \cdot e^{-b(N) \cdot v}$ ($a(N)$, $b(N)$, and $c(N)$ are linear function of N) fits the data from Łódź better (Figure 5.5).

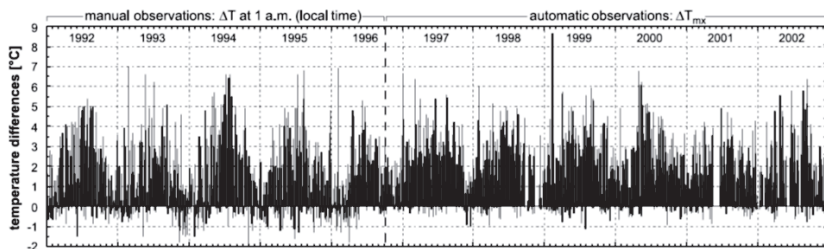


Figure 5.4. Urban-rural (MSM – Lublinek) temperature differences at night in Łódź in the period 1992–2002

Source: K. Fortuniak et al. (2006)

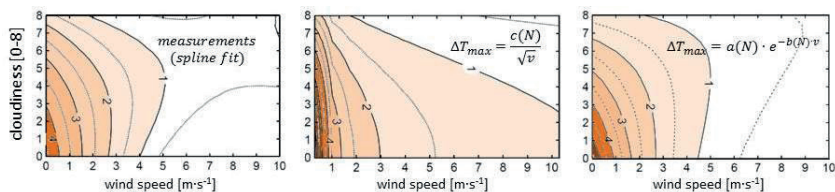


Figure 5.5. Maximum high-time urban rural temperature differences in Łódź in relation to wind speed and cloudiness

Source: K. Fortuniak (2003)

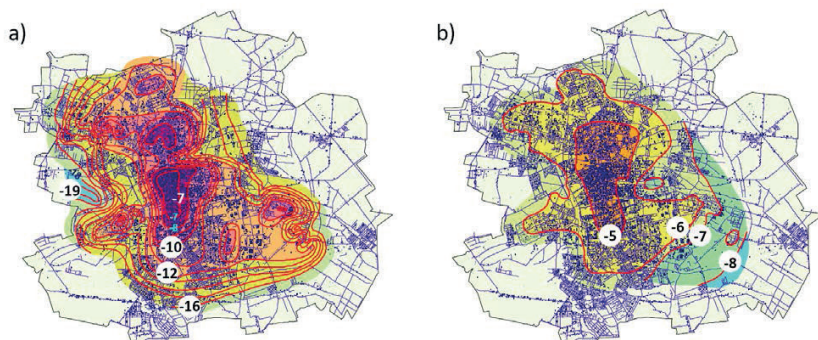


Figure 5.6. The strongest UHI observed in Łódź on 6th February, 1996 with temperature differences up to 12°C (a), and a typical generalized form of UHI in Łódź observed on 2th February, 1996 (b)

Source: elaboration based on K. Kłysik and K. Fortuniak (1999)

The strongest UHI was recorded in Łódź at night on 5th/6th February 1996 during the mobile measurements made by 5 cars (Kłysik and Fortuniak 1999). The centre of Łódź was up to 12°C warmer than the rural areas. Those extraordinary differences arose as a result of amplification of UHI by the advection of cold arctic air over the warm city with high thermal inertia and a significant anthropogenic heat flux. Under such extreme conditions, the UHI takes a multi-cellular form with a few separate hot spots

distributed over the area of the city following the building density (Figure 5.6a). A generalised form of UHI (Figure 5.6b) which develops under more usual conditions is more typical. The strongest UHI observed in Łódź is also a maximum recorded in Poland. The values noted in other big cities include: 10.4°C in Warsaw (Wawer 1992), 8.4°C in Wrocław (Szymanowski 2004), 8°C in Lublin (Kaszewski and Siwek 1998), and 7°C in Cracow (Lewińska et al. 1982).

Although many of recent works focus on UHI mitigation, it should be stressed that in general the UHI cannot be considered as a definitely negative phenomenon (at least under Polish climatic conditions). Due to the increase of temperature in the winter night (and in some cases during the day, too), it reduces heating fuel consumption, which is advisable from the perspective of mitigation of global warming and more sustainable development. Moreover, the UHI reduces the stability of urban atmosphere at night, which can prevent urban atmosphere from high concentration of air pollution emitted by surface sources. On the other hand, the increase of temperature in the summer can result in enlarged air conditioning energy consumption, but it is still rare in Poland. One of the potentially negative impacts of UHI is its interference with heat waves. An increased number of heat waves is one of potential global warming consequences (Wibig et al. 2009) which directly affect human health. During heat wave episodes, the city temperature at night remains a few degrees higher than the rural one. An analysis of the July 2006 heat waves in Łódź (Szcześniewska and Wibig 2008) showed that the UHI did not exert any influence on the length of heat waves defined on the basis of daily maximum temperature (so called hot day spell), but the heat waves defined on the basis of minimum temperature (tropical night spell) were evidently longer in the city centre. As a result, temperature in the city can remain above the acceptable threshold for a few consecutive days and the city population has no night-time rest from hot temperature.

5.4. Humidity and wind urban-rural differences

The influence of the city on other meteorological parameters is less obvious than in the case of temperature. The humidity contrasts must be analysed separately at least for the following two cases: relative humidity, f , and one of the absolute measures of water vapour concentration in the air. As the diurnal evolutions of different variables representing absolute characteristic of humidity are qualitatively similar, we have decided to use water vapour pressure, e , to illustrate the general rules.

The diurnal course of relative humidity is, in general, inverse to temperature. In consequence, the urban-rural relative humidity contrasts are usually negative. Especially at night or early morning, relative humidity in the city is significantly lower than in its surroundings (Figure 5.7). However, in contrast to temperature, for which favourable weather conditions always results in a well-developed UHI, the f evolution is less predictable. The f evolution shown in Figure 5.7 represents averaged values from several nights with good weather. Individual cases can considerably differ from this scheme. For example, a rapid increase of f in the rural site and its saturation in late evening together with a continuous f increase in the city during the night can result in a double minimum in the urban-rural contrast: first, at the beginning of the night, and second early in the morning. It can also happen that the f course in the urban site is parallel to the rural one. In this case, differences in temperature result in differences in absolute humidity (see Fortuniak et al. 2006 for discussion). The highest absolute differences in relative humidity can reach more than 40% under favourable weather conditions, but more typical values are of the order of 20–30%. It should be stressed that because of the temperature dependency of f these urban-rural differences do not necessarily mean that there is necessarily less content of water vapour in urban air.

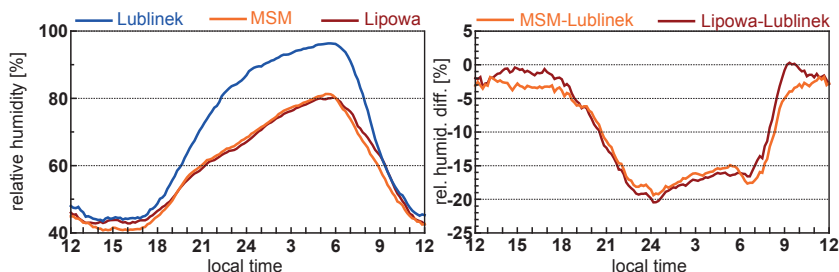


Figure 5.7. Typical evolution of relative humidity at rural (Lublinek) and urban (MSM, Lipowa) stations (left plot) and its urban-rural differences (right plot). Average values for 28 selected days from August in Łódź, 1997–2002

Source: K. Fortuniak et al. (2006)

The characteristic course of water vapour pressure during 24 hours is presented in Figure 5.8. It shows that the city is drier than its surroundings most of the time. Negative urban-rural differences start to vanish late in the evening because of dew condensation at a rural station (which uses water vapour from the near-ground air). In the city, dew formation is less intense because of higher temperature. In consequence, positive differences appear after midnight. Early in the morning, e grows rapidly at rural stations (because of dew evaporation and deep vertical mixing) and the differences become strongly negative. The range of differences under favourable weather conditions is from +4 hPa to –4 hPa in summer and below ± 1 hPa in winter. As in the case of relative humidity, this general pattern of water vapour pressure evolution can be broken even in the nights with an easily predictable course of UHI intensity, and individual realization of urban-rural differences of e can take an untypical shape.

Due to increased roughness, the mean wind speed, v , in the urban canopy layer is in general lower than in nearby open rural areas.

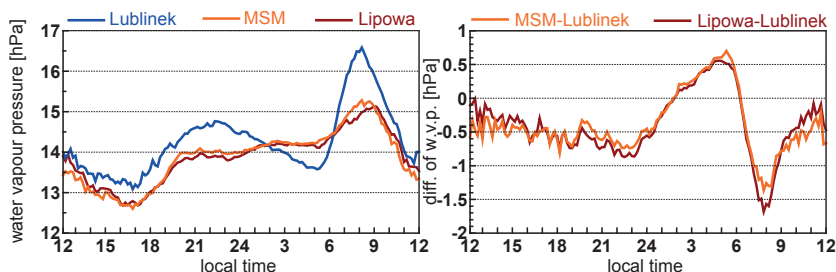


Figure 5.8. Typical evolution of water vapour pressure at rural (Lublinek) and urban (MSM, Lipowa) stations (left plot) and its urban-rural differences (right plot). Average values for 28 selected days from August in Łódź, 1997–2002

Source: K. Fortuniak et al. (2006)

Even if the physical mechanism is clear, the empirical investigations of the city influence on the wind field are complicated because of local effects within urban structures (e.g. wind channelling, turbulent eddies). In Łódź, the urban station, MSM, was located in a relatively open square which minimizes these microclimatic effects. The average wind speed at this site is lower than at the rural one by about 30–40% (Siedlecki 2003). However, under specific weather conditions the wind speed (in the sense of average value for a relatively long time e.g. the whole night) can be higher in the city centre than in rural areas. The urban breeze or increased turbulent momentum transport from the upper atmosphere is a potential reason of this effect. Under favourable weather conditions, one hour averaged wind speed at the MSM site can even be $1\text{--}1.5\text{ m}\cdot\text{s}^{-1}$ higher than at Lublinek. The probability that the wind speed (over a one hour averaging period) in the city centre will exceed its value at the rural station in Łódź decreases with the wind speed. Such situations occur in majority of cases for close to calm weather ($0 < v < 0.2\text{ m}\cdot\text{s}^{-1}$); they represent slightly less than 50% of cases when $v \approx 1\text{ m}\cdot\text{s}^{-1}$, and they become very rare when $v > 3\text{ m}\cdot\text{s}^{-1}$ (but they still can be observed for rural wind of up to $5\text{ m}\cdot\text{s}^{-1}$).

5.5. Radiation processes

The most evident influence of the urban atmosphere on the radiation is the reduction of downward shortwave radiation, k , by air pollution. This parameter has been intensively studied and the first Polish work on this subject comes from the beginning of 20th century (Gorczyński 1913). It is well accepted that the solar radiation is reduced about 10% in the case of annual totals, about 20% for monthly totals and more than 30% for selected days (Landsberg 1981, Oke 1995). The measurements made at the Lipowa and Lublinek sites show that k is on average about 7% lower in the centre of Łódź (Podstawczyńska 2007, 2010). The weakest attenuation is observed in the summer (about 5% with minimum in May about 3%) and the strongest in winter (about 15%). In extreme situations, the urban-rural difference in daily totals can reach 40% (Figure 5.9). The differences expressed in $\text{MJ}\cdot\text{m}^{-2}$ per day are higher in the summer because solar radiation is the strongest in this season. The daily totals of k in the centre of Łódź are lower by $0.79 \text{ MJ}\cdot\text{m}^{-2}$ in June and $0.22 \text{ MJ}\cdot\text{m}^{-2}$ in January. The annual totals of energy received as a shortwave radiation at the Lipowa site are lower by $179.4 \text{ MJ}\cdot\text{m}^{-2}$ (Podstawczyńska 2007, 2010).

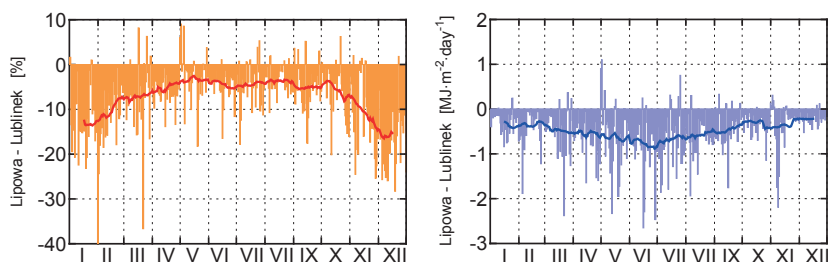


Figure 5.9. Absolute (in $\text{MJ}\cdot\text{m}^{-2}$ per day – upper day) and relative (in % – lower plot) urban-rural differences in daily totals of incoming shortwave radiation, k_{\downarrow} , Łódź, years 1998, 2000, 2001

Source: A. Podstawczyńska (2007)

The absorption of the incoming shortwave radiation is determined by the surface albedo. The measurements made on two EC towers at Lipowa and Narutowicza show that this parameter for the central part of Łódź can be estimated to be at a level of 8–10%, with slightly higher values at the Narutowicza site (Pawlak 2009). These values are lower than the one suggested for the cities by T.R. Oke (1995). It is a consequence of the high portion of dark tarred roofs and asphalt roads dominating in the artificial surface cover in Łódź. Like in other cities, the albedo is angular dependent with lowest values for high Sun elevation (Figure 5.10). It manifests in the typical U-shaped diurnal course of this parameter. The dependence of the albedo on the inclination of solar beam is a result of both the physical properties of the covering materials and urban geometry. K. Kłysik (1997) showed that U-shaped albedos characterise the typical roofs of buildings in Łódź. The urban geometry itself not only reduces the total albedo of the city due to radiation absorption after multiple reflection in urban structures, but also modifies the daily course of this parameter. Numerical estimation (Figure 5.11) shows that the multiple reflection process, even in the simple structures such as an idealised urban street canyon, can result in complicated diurnal evolution of this parameter (Fortuniak 2008, Pawlak 2009).

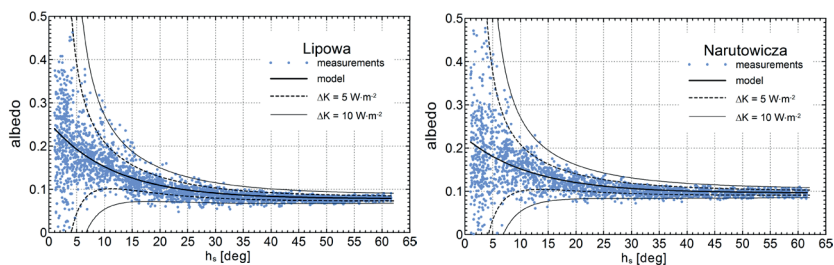


Figure 5.10. Urban albedo measured at the Lipowa and Narutowicza sites as a function of Sun height, h_s , together with exponential fit and accuracy limits for two presumed sensors accuracy (5 and 10 $\text{W}\cdot\text{m}^{-2}$)

Source: K. Fortuniak (2010)

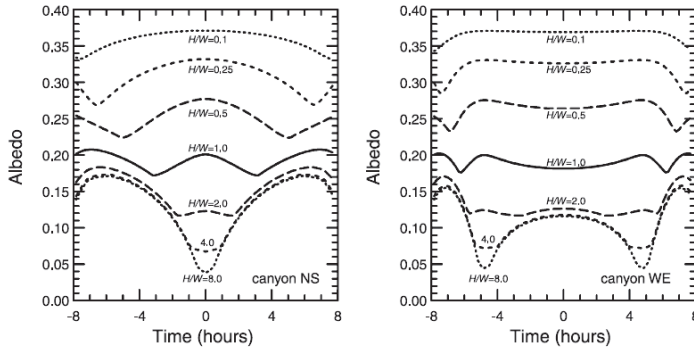


Figure 5.11. Modelled diurnal course of the effective albedo of an urban canyon with uniform surface albedo equal 0.4 and with building height to street width ratio, H/W , varying from 0.1 to 8.0 on 22th June for north-south (left) and east-west (right) oriented urban canyon at latitude 55°N

Source: K. Fortuniak (2008)

The influence of the city on long-wave radiation is poorly documented. On the basis of only a few available papers it can be estimated that downward longwave radiation, L , in urban areas is about 6–10% higher than at the surroundings. A preliminary comparison of the data from the Lipowa site and the field station localised at a distance of about 50 km east from Łódź shows that in fine weather L can be about 10% higher than in Łódź. Similarly, the same data show that upward longwave radiation, L , from the city centre can be raised by about 12%.

5.6. Urban energy balance

The energy balance for the urban areas includes more components than in the classical form. It can be expressed as (Oke 1988):

$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A$$

where Q^* is the net all-wave radiation, Q_F is the anthropogenic heat flux, Q_H is the turbulent sensible heat flux, Q_E is the turbulent latent heat flux, ΔQ_S is the net storage heat flux (the heat flux into the ground is incorporated in this flux), and ΔQ_A is the net horizontal heat advection. Among them, only Q^* , Q_H , and Q_E can be directly measured. Anthropogenic heat flux is usually estimated on the basis of the energy used for building heating/cooling, transport, industry or even human metabolism. The advection term is assumed to be negligible for a properly chosen measurement site (fetch analysis before site setting). The net storage term is the most difficult to evaluate and in practice it is even assumed to be a rest from the energy balance equation.

Restrictions of the site location, complicated instrumentation and data processing cause that the measurements of the turbulent fluxes are quite rare in urban areas. The eddy-covariance method is in practice the only one which can be applied for reliable turbulent flux measurements in the cities. However, it needs sensors which are able to measure wind components, temperature and humidity with a frequency of at least 10 Hz. Such instruments have become commercially available only in recent years. To get results representative for an averaged urban area, the sensors must be placed at the constant flux level, above the so called blending height, which is usually more than twice the average building height. The sensor must be mounted on a thin mast to avoid flow distortions. Moreover, the area around the site should be relatively homogenous with a well-defined roof level. Both measurements sites in Łódź fulfil these conditions. Turbulent fluxes are calculated with the standard procedure used by other eddy-covariance groups (Aubert et al. 1999). Figure 5.12 shows an average diurnal course of energy balance components at the two sites in Łódź. A typical feature of urban energy balance is a relatively large portion of available energy (Q^*) used for sensible heat flux, Q_H (Figure 5.12). For a densely built-up city centre of Łódź, Q_H is usually about two times larger than Q_E at noon hours. The inversed situation is characteristic for natural grassy surface in the Łódź surroundings, while in the residential or post-industrial areas in Łódź both fluxes are comparable (Offerle et al. 2006b). On average, Q_H reaches about $150 \text{ W}\cdot\text{m}^{-2}$ at noon in

summer both at the Lipowa and Narutowicza sites. The latent heat flux, which dominates in energy partitioning in rural areas, remains at the same time at a level of $80\text{--}100\text{ W}\cdot\text{m}^{-2}$. In winter, both fluxes are very small, but at noon hours Q_H clearly dominates also in this season (Offerle et al. 2006a, Fortuniak 2010, Fortuniak et al. 2012).

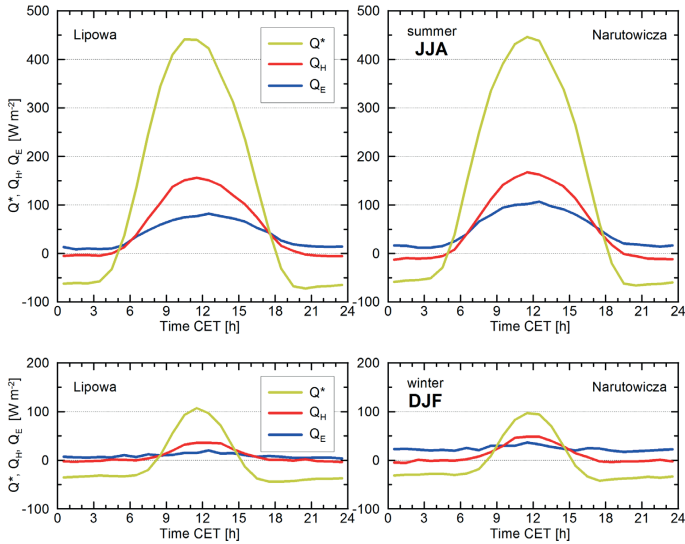


Figure 5.12. Average diurnal courses of energy balance components in summer and in winter at two measurement sites in Łódź calculated on the basis of all available data from the period 2005–2010

Source: K. Fortuniak et al. (2012)

The highest values of Q_H have been recorded in Łódź in summer days and they can exceed $300\text{ W}\cdot\text{m}^{-2}$. In the long term records from Łódź, it is also possible to find a few examples when Q_H remained negative all day long (during warm advection after a cold period). A characteristic feature of urban energy balance, observed also in Łódź, is that Q_H remains positive in the evening, when radiation balance turns negative, which can be attributed to the large heat storage in the urban fabric. In contradiction to many other cities, we record a large number of cases when $Q_H < 0$ at night.

The highest values of Q_E recorded in Łódź can reach about $150 \text{ W}\cdot\text{m}^{-2}$, but it must be stressed that these values represent fine weather conditions, whereas the maximum values are expected immediately following summer showers when rain falls on the hot urban surface. Unfortunately, the water drops remaining on the sensors of the open-path eddy-covariance systems cause the data to be unreliable in such situations. The latent heat flux in Łódź remains positive over the whole 24 hours and the cases when $Q_E < 0$ are extremely rare.

Both EC measurements sites in Łódź are located in the core of the old centre with similar urban structure. Moreover, in both cases the source areas, defined as the areas contributing to the measured fluxes to the greatest extent, form roughly a circle with a diameter of about 1 km around each site location. In consequence, the results at both sites should be comparable and characteristic for the central part of the city. Indeed, the fluxes presented in Figure 5.12 are similar for both sites. It is additionally confirmed by measurements made using a scintillometer on the path more than 3 km over the city centre (Fortuniak et al. 2012, Zieliński et al. 2012, Zieliński et al. 2013). The comparison of Q_H measured in Łódź by both techniques (scintillometry and eddy-covariance) shows a very good agreement (Figure 5.13).

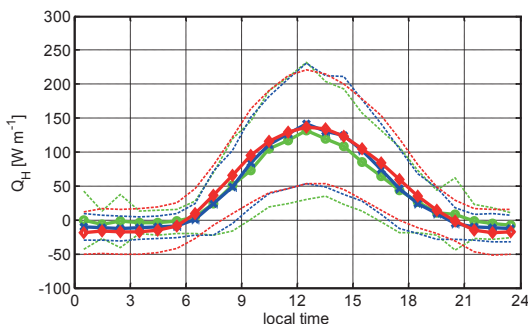


Figure 5.13. Diurnal evolution of sensible heat fluxes calculated from scintillometer (free convection assumption – red line), measured at the Lipowa (green) and Narutowicza (blue) sites. Mean value \pm standard deviation for the period 11.06.2010–5.11.2010

Source: K. Fortuniak et al. (2012)

Because of different source areas and surface inhomogeneity, the data do not need to be similar, especially in individual cases, however, averaging for different wind directions and stability classes gives results characteristic for relatively large areas of Łódź which, in general, have a similar surface cover. Thus one can expect comparable results. The universality of the results is also confirmed by the fact that the surface parameterisation worked out based on the data from Łódź (Fortuniak 2003a, b) also works well for other cities (Grimmond et al. 2010, 2011).

5.7. Carbon (CO₂ and CH₄) fluxes and radon concentration

Cities can be considered as a hot spots of emission of the main greenhouse gasses including CO₂ and CH₄. While cities cover only 2% of the Earth's surface, they produce more than 90% of anthropogenic carbon dioxide emissions. The estimation of the role of urban areas in global carbon production based on the inventory of emissions has a number of limitations in terms of their temporal and spatial resolution. The net exchange including surface emissions and absorption in the photosynthesis process must be evaluated by direct measurements using micrometeorological techniques such as eddy-covariance. In Łódź, the measurements of net CO₂ exchange were made at different sites in short experiment in the years 2002–2003 (Offerle et al. 2006b, Pawlak et al. 2011b, 2012), and have been continued since 2006 at the Lipowa site (Pawlak et al. 2011a, b, 2012). The results from the short experiments show the negative (downward) flux above grassland reaching $-2.9 \text{ g m}^{-2} \text{ day}^{-1}$ in summer 2003 (the same time mean flux at Lipowa was $20.5 \text{ g m}^{-2} \text{ day}^{-1}$). In the residential area daily totals were about $12 \text{ g m}^{-2} \text{ day}^{-1}$ lower than at Lipowa and in the post-industrial area about $10 \text{ g m}^{-2} \text{ day}^{-1}$ lower. The long-term measurements from Lipowa (Pawlak et al. 2011a) show that regardless of a season, positive (upward) fluxes amounting to $0\text{--}15 \text{ } \mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$

prevail in the data, which means that CO_2 emission prevails over its uptake. Regardless of the season, except summer, the maximum flux occurred during the day and the minimum during the second part of the night (Figure 5.14). In summer, intense photosynthesis during the day and reduced car emissions caused by the holiday period result in a daily minimum in sunlight hours, but even in these situations the net CO_2 flux remains positive on average (net emissions from the surface). The weekly rhythm of traffic in the surroundings of Lipowa results in differences in CO_2 flux between weekends and weekdays (Figure 5.14).

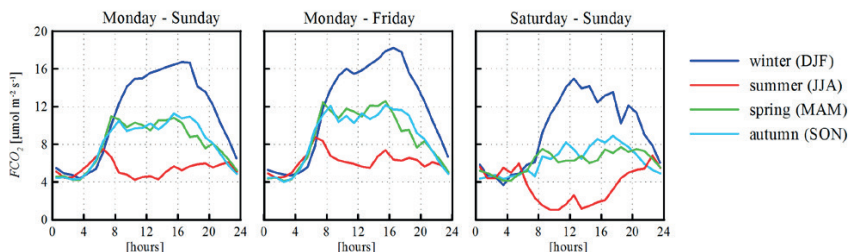


Figure 5.14. Mean diurnal course of net carbon dioxide flux, FCO_2 , in seasons at the Lipowa site calculated separately for full weeks, weekdays and weekends for the period July 2006 to May 2011

Source: K. Fortuniak et al. (2012)

Knowledge about the net emissions of methane from the cities is very limited. The measurements of the methane flux in Łódź were initiated in summer 2013. The EC system at the Lipowa site was extended by a new Li-7700 sensor allowing for the open-path CH_4 flux measurements. Only very preliminary results are available up to now. They suggest that the emissions in the summer are at a level of $30 \text{ nmol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$.

Some recent studies on local climate in Łódź focus on radon (^{222}Rn) concentration, its differences between urban and rural areas and relation to the weather parameters (Podstawczyńska et al. 2010, Podstawczyńska 2013). Radon gas is a significant source of

natural radioactivity in the near ground air layer. In Poland, its inhalation is responsible for over 40% of the annual effective dose of ionizing radiation. The ^{222}Rn concentration was measured at a height of 2 m above ground level for more than two years at the MSM and at the rural site Ciosny located 25 km to the north from Łódź. The average ^{222}Rn concentrations at the investigated sites are representative for continental areas, i.e. $4.8 \text{ Bq} \cdot \text{m}^{-3}$ (MSM), $5.8 \text{ Bq} \cdot \text{m}^{-3}$ (Ciosny). In summer, the daily course of ^{222}Rn concentration at 2 m a.g.l. is an inversion of air temperature course (Figure 5.15). During the day, the ^{222}Rn concentration is similar at both sites, but the night-time maximum is much stronger at the rural site, which can be attributed to the more stable stratification there. In the city centre, the thermal stratification is less stable during the night due to the UHI phenomenon. Moreover, the wind speed can be stronger in the city in close to calm situations. Both processes increase turbulent mixing and protect the city centre from high concentrations of ^{222}Rn . In winter, the diurnal course of ^{222}Rn concentrations is poorly pronounced and its values are close to the long term averages.

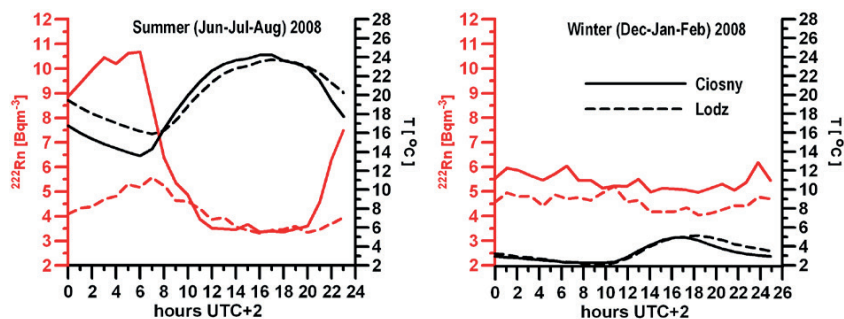


Figure 5.15. The mean of 24 h pattern of ^{222}Rn concentration in the air and air temperature at 2 m above the ground at the rural (Ciosny) and urban (MSM) stations in summer and winter 2008

Source: A. Podstawczyńska et al. (2010)

5.8. Conclusions

The results presented in the work show the selected features of local climate modification caused by urbanisation in Łódź, Central Poland. The city structure is similar to many other mid-European towns, but the influences of urbanisation on local climate are not affected here by other factors. Thus, the outcomes of presented investigations can be generalised for many cities of the region. The findings about the urban heat island are similar to those of other cities and they confirm the general rules about the UHI phenomenon, its spatial distribution and temporal variations (see Arnfield 2003 for a comprehensive review). Similarly, the influence of the city on incoming shortwave radiation in Łódź simply quantify well established relations. More unique are the studies on the albedo and the influence of surface geometry on the absorption of radiation. The influence of the town on humidity is more disputable. On the average, our data confirm the findings on the urban-rural contrasts of these elements, but they also show that unlike the UHI evolution, the diurnal course of humidity differences can take different form even in favourable weather conditions. The measurements of turbulent fluxes of sensible and latent heat, carbon dioxide and methane are unique in Poland and one of the few in Europe; thus they just provide new data and extend our understanding of poorly known processes. At the present stage, it is hard to evaluate if these result are case-specific or more general. The comparison with other cities is problematic because of a small number of similar works – there are several concerning urban energy balance, very few on carbon dioxide flux, and almost none about the flux of methane.

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